DETERMINING VERTICAL SOIL-WATER FLUX IN GLACIATED TERRAINS USING A CONVECTIVE HEAT FLUX MODEL AND MEASURED TRANSIENT SOIL THERMAL PROPERTIES

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Introduction

The value of this ongoing work is to develop a data-driven convective flux model that can acheive real-time percolation estimates from vadose-zone monitoring networks

Several workers have applied water flux models based on convective heat-transfer principles and measured temperature profiles to quantify vertical water movement through unsaturated soils.

Flux estimates can vary significantly due to uncertainty in soil thermal properties such as thermal diffusivity, thermal conductivity, and soil volumetric heat capacity and their relationship to changing degrees of saturation.

In this study, soil temperature profile data is combined with in situ measurements of soil thermal properties to estimate both upward and downward water fluxes through soils developed in glacial parent materials.

Model development

Tabbagh et al. (1999) considered the heat flow equation for a homogenous soil for determining recharge in the unsaturated zone:

$$\alpha\frac{(\partial^2 T)}{(\partial z^2)} - v\frac{(\partial T)}{(\partial z)} - \frac{(\partial T)}{(\partial t)} = 0$$

$\alpha = thermal\ diffusivity\ (m^2/s)$

$T = soil\ temperature\ (°K)$

$z = depth\ (m)$

The heat flow equation can also be written as a finite difference 1-D solution:

$$0 = \alpha\left(\frac{T_{i,j+1} - 2T_{i,j} + T_{i,j-1}}{\Delta z^2}\right) - v\left(\frac{T_{i,j+1} - T_{i,j}}{\Delta z}\right) - \left(\frac{T_{i,j} - T_{i-1,j}}{\Delta t}\right)$$

$T_{i,j+1} = highest\ temp.\ (0.9m)$

$T_{i,j} = middle\ temp.\ (1.2m)$

$T_{i,j-1} = lowest\ temp.\ (1.5m)$

$\Delta z = temp.\ sensor\ spacing\ (m)$

$\Delta t = time\ step\ (s)$

The velocity term (v) can also be expressed as it relates to volumetric flow rate and volumetric heat capacity:

$$v = (uC_w)/C_v$$

$C_w = fluid\ volumetric\ heat\ capacity\ (J/m^3K)$

$C_v = soil\ volumetric\ heat\ capacity\ (J/m^3K)$

$C_v = \lambda/\alpha$

$\lambda = thermal\ conductivity\ (W/mK)$

$u = volumetric\ flow\ rate\ (m/s)$

Our modelling effort entails monitoring the soil temperature, thermal conductivity, and thermal diffusivity parameters and solving for volumetric flow rate to arrive at flux, which can be either upward or downward depending on the sign of the temperature derivatives. Previous workers (Benjoudi et al., 2005) have used inverse-derived thermal properties to determine both upward and downward water fluxes using soil-temperature profiles.

Data collection

In-situ thermal properties measurement

The Hukseflux TP01 utilizes dual thermopiles providing radial temperature measurement around a heating wire to determine thermal conductivity (λ) and diffusivity (α).

V ~ 1/λ

t ~ α

1. Following an initial transition period, temp. rise close to the heating element is a function of the thermal conductivity of the soil medium (λ) and is no longer dependent on heat capacity.

2. The time response of the probe during the transition period ($t\lambda_x$ in fig. below) is proportional to the diffusivity of the surrounding medium.

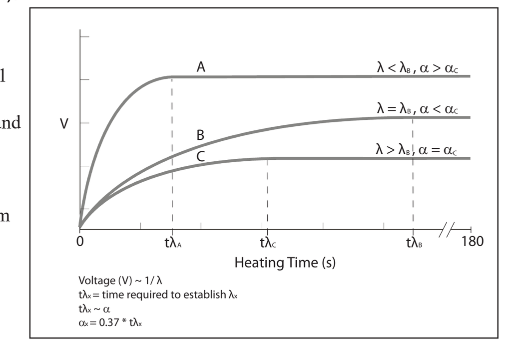

Figure 1. TP01 thermal conductivity and diffusivity measurement approach (modified from Hukseflux, 2012)

$$V - V_0 = \underbrace{(E_\lambda Q/\lambda)}_{1.}\ \underbrace{F(\alpha t)}_{2.}$$

V = thermopile voltage reading
V_0 = initial voltage
Q = power applied
E_λ = factory calibration constant
t = time
F = function equal to 1 for large αt

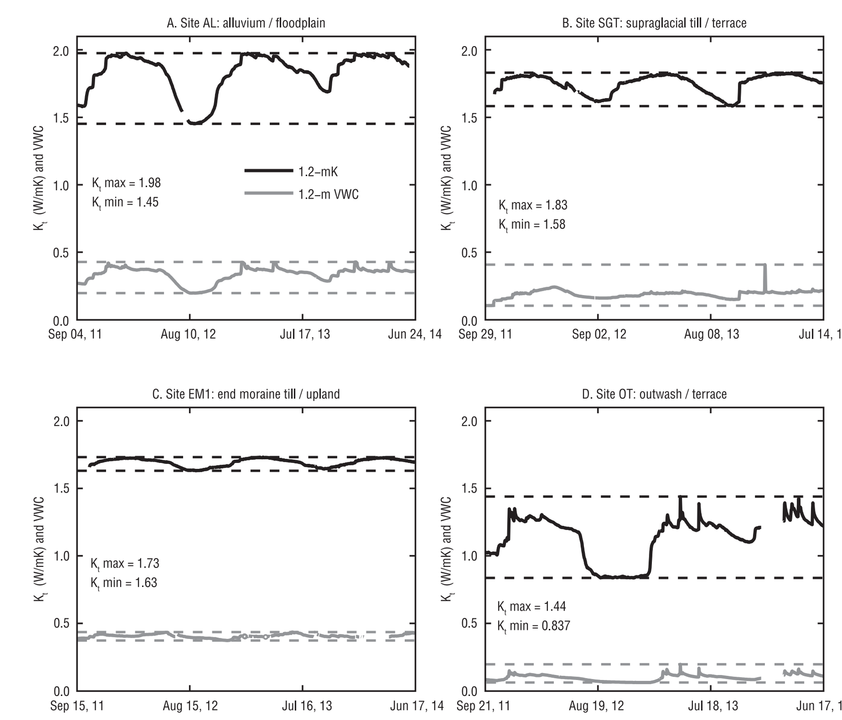

Figure 2a-d. Measured transient thermal conductivity plotted with volumetric water content (VWC) measured at coinciding 1.2-m depth. Figure modified from Naylor et al., 2015.

Soil temperature measurement

Soil temperature is measured at 0.3-m depth intervals using Campbell Scientific CS650 soil water content reflectometers that measure soil temperature with 0.1 °C accuracy and 0.001 °C resolution.

Study area / monitoring sites

Hydrogeologic setting

Table 1. Monitoring sites, soil parent materials, topographic settings, and land use (sites with thermal properties data and previously developed HYDRUS soil-water dynamics models are marked by red boxes).

Site label	Soil parent material	Terrain	Land use / vegetation
AL	alluvium / lacustrine	floodplain	prairie / mixed grasses and wildflowers
OT	glacial outwash	terrace	conservation / mixed grasses
SGT	glacial till (supraglacial)	terrace	row crop / corn and soybean rotation
GM	glacial till (ground moraine)	plain	turf grass
EM1	loess / glacial till (end moraine)	hill crest	turf grass
EM2	glacial till (end moraine)	hill crest	prairie / mixed grasses and wildflowers

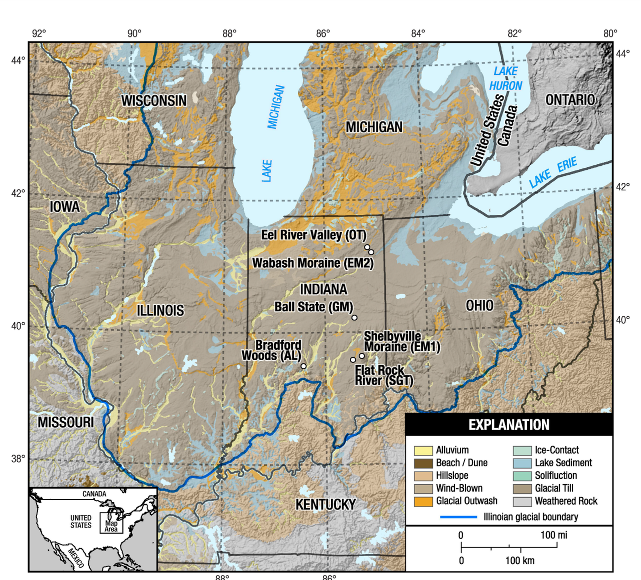

Figure 3. Geologic map of the Great Lakes region (GLR) showing site locations in Indiana. Additional details regarding the monitoring sites and soil data can be accessed at: http://igs.indiana.edu/CGDA/waterBalanceNetwork.cfm.

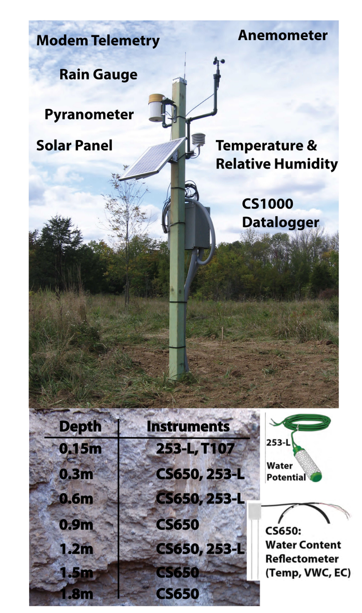

Figure 4. Micrometeorological and vadose-zone instruments installed at each site. Additional details regarding thermal properties and vadose zone hydrologic monitoring are provided in Naylor et al. (2015) and Naylor et al. (2016).

Climatological setting

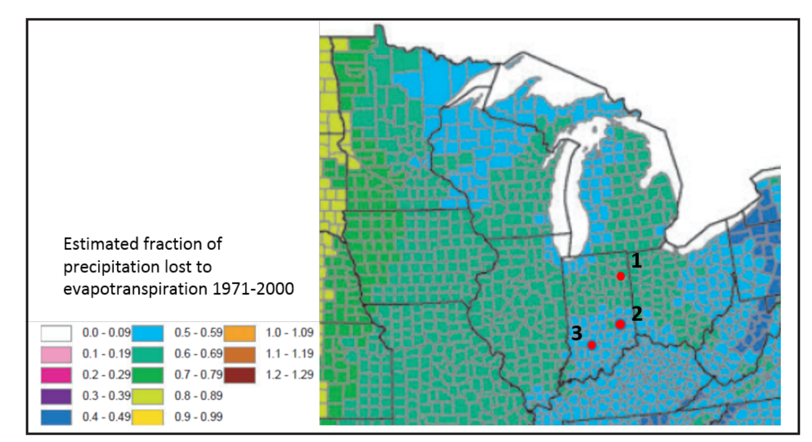

Figure 5. Estimated ratio of actual evapotranspiration to precipitation (P) for the GLR from Sanford and Selnick (2013). Reference stations that are used to compare 30-year normal P with site measurements are shown with red dots.

Table 2. 30-year normal precipitation at reference sites.

Reference station	Site # from figure 5	30-year normal mean annual P (cm)	Mean annual snow (cm)	Sites compared
Fort Wayne	1	97.4	85.1	EM2, OT
Rushville	2	113.0	35.1	SGT, EM1
Martinsville	3	113.6	40.9	AL

- Approximately 40-69% of precipitation is lost to evapotranspiration in the GLR (Fig. 5).
- Diffuse recharge is the dominant recharge mechanism in these humid settings (Scanlon et al., 2002).
- The water table is commonly less than 5 m below the ground surface in the GLR, so percolating soil water readily enters the ground-water flow system as recharge.

Water flux method 1: Conventional numerical modeling of Richards equation

Soil-water dynamics simulated with HYDRUS 1D (Šimůnek et al., 2005)

- Previously published models (Naylor et al., 2016) numerically solve Richards equation for unsaturated flow
- Flow equation includes sink term to account for water uptake by roots (inputs are leaf area index and root depth)
- Surface infiltration is simulated when precipitation exceeds potential evapotranspiration
- Runoff is simulated when precipitation exceeds infiltration during wet periods when surface is saturated
- Hydraulic parameters were determined using an inverse modelling approach described in Naylor et al. (2016). Soil moisture data were used for model calibration.
- The groundwater recharge estimates were determined by flux at the water table for all sites except the Eel River outwash site (OT) where flux at the base of the model (3m) was used to represent recharge.
- For comparison with convective flux estimates in this study, we use HYDRUS model fluxes at the 1.2-m depth where the thermal properties are measured and the finite difference solution is centered.

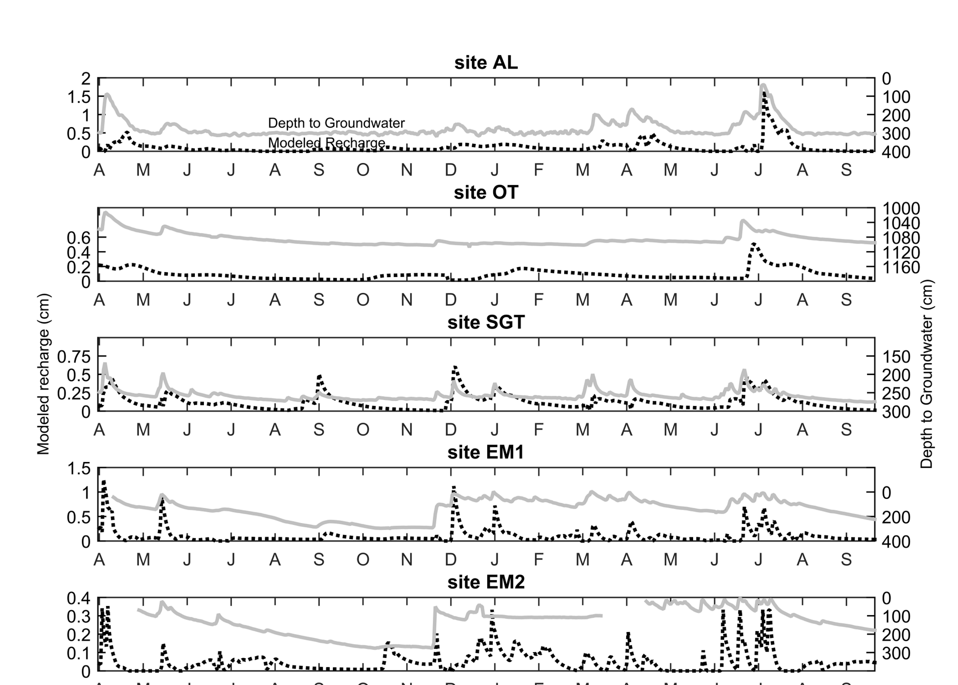

Figure 6. Measured groundwater levels and HYDRUS modeled daily recharge flux (cm d-1) between April 2014 and September 2015.

Water flux method 2: Data-driven convective heat transport model

- Excessively high magnitude flux estimates coincide with "equinox temperature reversals" when ground temperatures at adjacent depths "flip" during the spring and fall of each year (figure 7)
- During the "equinox temperature reversals", the depth-temperature derivative approaches zero. We address this numerical artifact by using limits surrounding zero for the depth-temperature derivative when flux is set equal to zero
- Although the depth-temperature limits resolved many of the high-magnitude fluxes, spuriously large negative fluxes still occurred as shown in figure 8 for the Eel River site. To address this issue, we limit upward flux to the daily potential evapotranspiration (PET) value calculated from site-specific micrometeorological data.

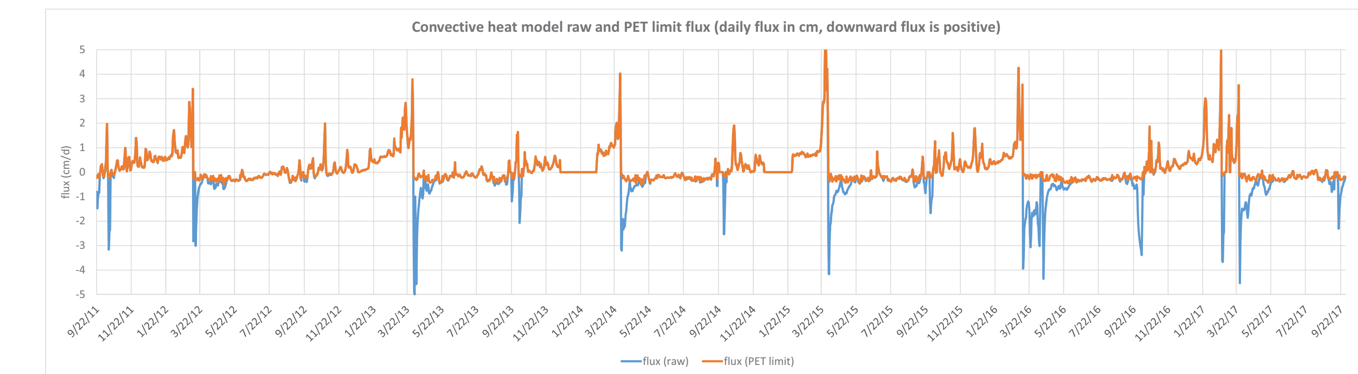

Figure 8. Convective model flux results for the OT site from September 2011 to September 2017 with and without daily PET limit placed on upward water flux (negative).

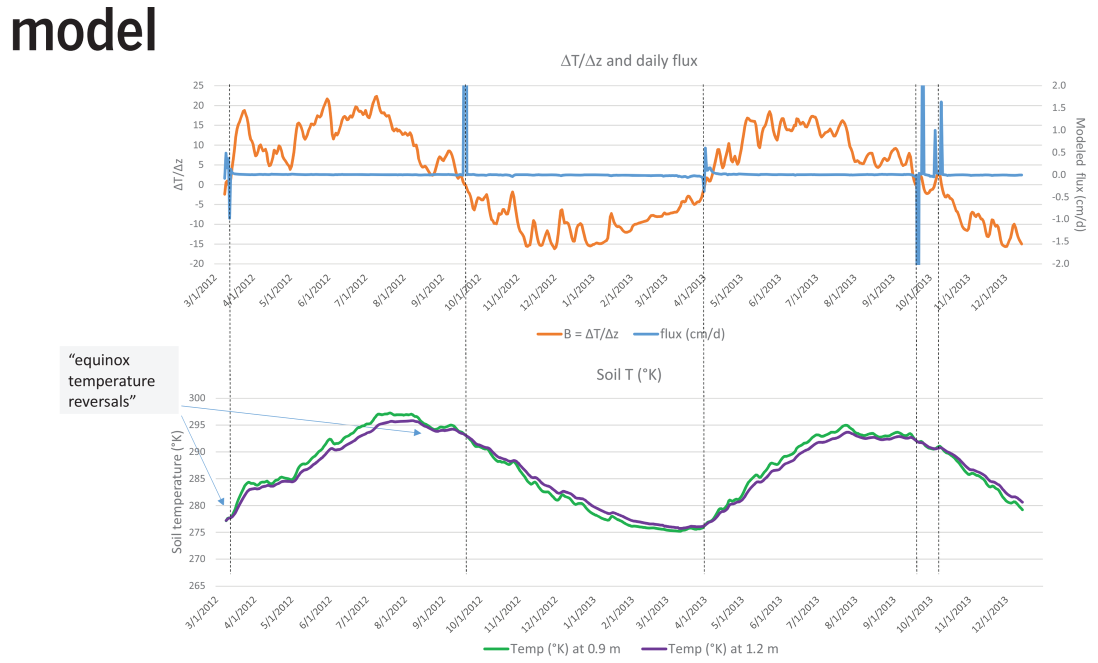

Figure 7. Convective model raw daily water flux values plotted with the depth-temperature derivative and soil temperature data at 0.9 and 1.2-m depth that are used to calculate the derivative for the advective flux term in the governing soil heat flow equation.

Results

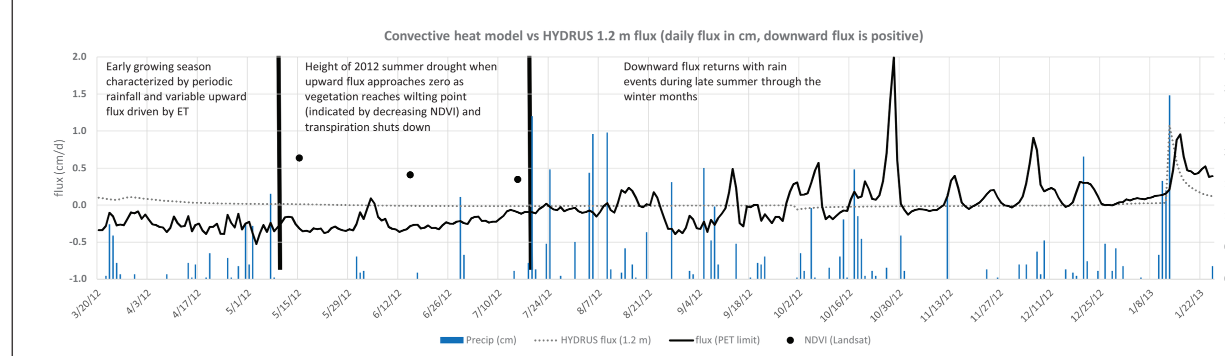

Figure 9. Convective model flux results for the OT site during and following the 2012 drought plotted with HYDRUS flux estimates at 1.2-m depth and precipitation. Monthly composite Landsat Normalized Difference Vegetation Index (NDVI) values are also plotted for May, June, and July.

- Consistent with Landsat vegetation data for the Eel River site that indicates degrading vegetation during the 2012 drought, upward flux estimates approach zero during the May - July drought period (figure 9)
- The timing and magnitude of downward flux estimates are generally consistent with HYDRUS flux simulations during the 2013 recharge season (figure 10)
- Although precipitation-driven downward flux events are still apparent in the early spring convective flux results at the Eel River site, suspiciously high flux estimates are possibly caused by annual temperature shifts impacting the diffusive heat transport term in the governing equation

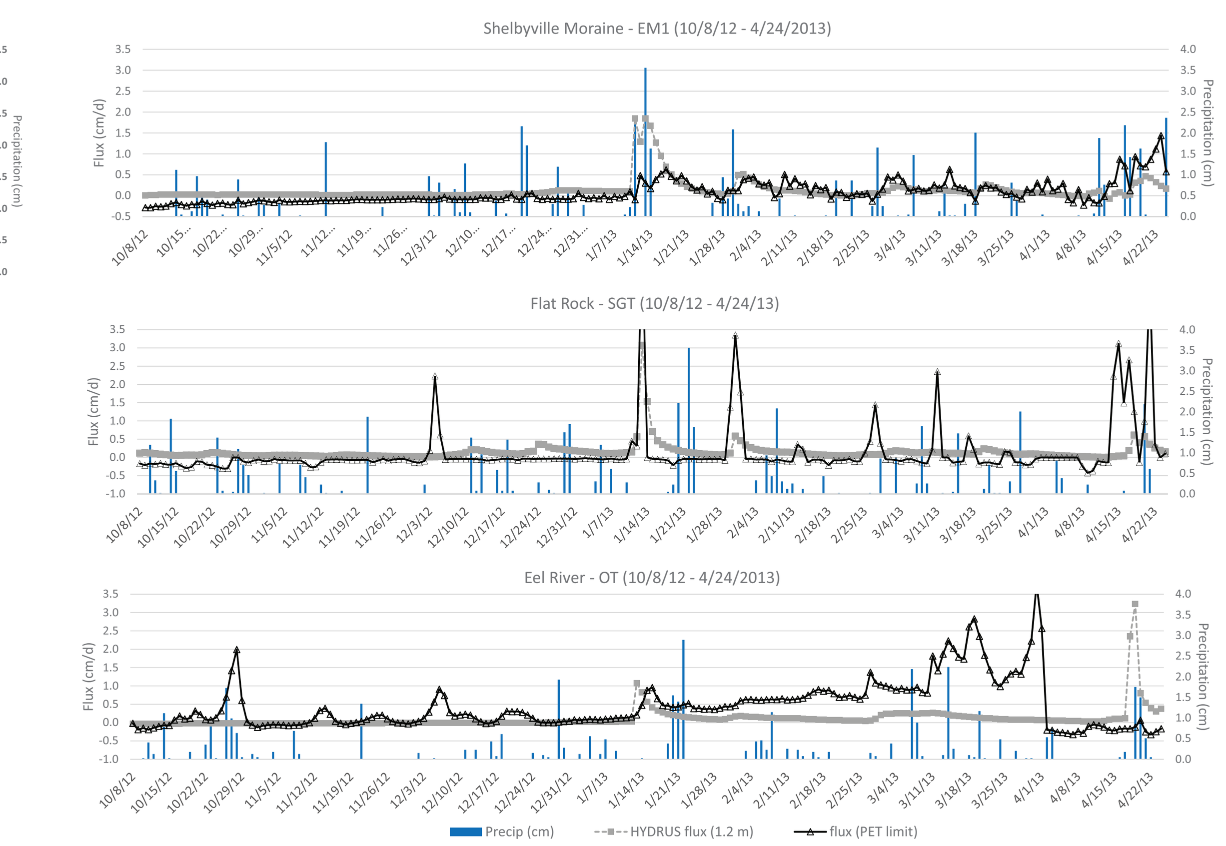

Figure 10. Convective model daily flux estimates plotted with HYDRUS daily flux for the Shelbyville Moraine (EM1), Flat Rock (SGT), and Eel River (OT) sites during the recharge season of the 2013 water year.

Discussion / conclusions

- Preliminary results suggest that transient soil thermal thermal properties data can be used in conjunction with soil temperature profile data to accurately simulate vertical soil-water fluxes and groundwater recharge
- Commulative flux during the recharge season shown in figure 10 at the Flat Rock (SGT) site was within 10% of previously published groundwater recharge estimates from a HYDRUS 1-D model
- Future work will entail soil temperature signal processing in order to isolate temperature perturbations from annual cycles and improve the model for continuous flux determinations

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